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Greenhouse evaluation of tomato cultivars across ripening stages for selection of superior breeding genotypes

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ABSTRACT

Tomato (*Solanum lycopersicum*) is a globally important vegetable crop, making the development of high-yielding, high-quality, and market-oriented cultivars a key breeding goal. This research investigated fruit yield and quality in 25 commercial tomato cultivars during three fruit ripening stages (S1: green, beginning of ripening, and S3: fully ripened under greenhouse conditions at Shahid Bahonar University of Kerman. A randomized complete block design (RCBD) with three replications was used. Measured traits included total soluble solids (TSS), fruit firmness (FF), color indices (a*, b*, and L*), pH, fruit length (FL), fruit width (FW), fresh and dry fruit weights (FFW, DFW), internode length (IL), and total yield (YLD). Significant genetic variation was detected among cultivars for most traits, except pH, FW, and b* at S3, indicating high potential for selection. The results provided practical cultivar recommendations based on market demands. For the fresh market, 'Sylviana', 'TM10857', and 'GS12' were notable for their high TSS, appealing color, and moderate firmness, while 'Goldy' and 'Aragon' exhibited balanced traits. For processing, 'Izmir', 'Sama', and 'Bernetta' were preferred due to their deep red color and lower TSS, and 'SV4129TH' and 'Bassimo' offered a desirable balance of firmness and color. Dual-purpose cultivars like 'SVH4040', 'SV3725', and 'RFT112' demonstrated strong yield, firmness, and TSS performance, making them adaptable choices for fresh markets and processing industries. Overall, this study provides valuable insights for breeding and selection of tomato cultivars aligned with both consumer and industry needs.

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Abbreviations: Redness (a^*), Yellowness (b^*), Dry fruit weight (DFW), Fruit firmness (FF), Fresh fruit weight (FFW), Fruit length (FL), Fruit width (FW), Internode length (IL), Lightness (L^*), Total soluble solids (TSS), Total yield (YLD)

1. Introduction

Tomato (*Solanum lycopersicum*) is one of the most important horticultural crops worldwide, valued for its high nutritional content and essential role in human nutrition. Belonging to the Solanaceae family (Kumar *et al*., 2020), tomato ranks among the top vegetable crops, with a global production of approximately 192 million tons in 2023, representing a 25% increase since 2010 (FAO, 2023). As a widely cultivated irrigated crop, tomatoes are rich in essential nutrients, including vitamins, minerals, and bioactive compounds, and have been associated with a reduced risk of cardiovascular diseases and certain cancers (Kumar *et al*., 2020; Ciptaningtyas *et al*., 2022). Tomato quality is a complex trait determined by various factors, including appearance, flavor, nutritional value, processing suitability, and storage characteristics (Keabetswe *et al*., 2019).

Genotypes exhibit substantial variation in size, shape, color, growth, yield, and physiological traits, reflecting their extensive genetic diversity (Vela-Hinojosa *et al*., 2019). These variations directly influence consumer acceptance and marketability. Previous studies have shown that fruit yield and quality traits, such as color, firmness, and total soluble solids (TSS), are strongly influenced by genotype and ripening stage (Helyes *et al*., 2006; Avdikos *et al*., 2021; Kasnazany *et al*., 2021). Evaluating these traits across multiple ripening stages provides critical information for identifying superior cultivars and guiding market-oriented breeding strategies.

While fruit yield is a crucial criterion for selecting superior cultivars, its high sensitivity to environmental conditions limits its reliability as a sole selection index. Instead, prioritizing more stable traits those less affected by environmental fluctuations can enhance the precision and effectiveness of the selection process (Fahmideh *et al*., 2024). Key quality indicators include fruit color components, firmness, and TSS, which are particularly vital in defining tomato quality and directly influence consumer preference and market acceptance (Kumar *et al*., 2022).

Globally, tomatoes are harvested at different maturity stages to align with market preferences; some regions favor the breaker stage, while others prefer the mature-green stage. The mature-green stage represents a physiologically mature yet pre-ripe phase, marked by a green hue with slight whitening. Research suggests that harvesting at this stage can extend shelf life and improve distribution durability. Consumers often judge tomato maturity based on color and firmness, with fully bright red fruits generally commanding higher marketability (Causse *et al*., 2010; Ciptaningtyas *et al*., 2022). Beyond visual appeal, TSS plays a crucial role in determining flavor, texture, and processing yield (Avdikos *et al*., 2021).

Studies on tomato genotypes have revealed significant genetic diversity in traits such as fruit weight, TSS content, and yield (Henareh and Pierasteh, 2012). For example, an evaluation of four tomato cultivars identified ‘Hawramanas’as having the highest shape index, firmness, and total sugar content, while ‘Sktan’ excelled in fruit yield per plant (Kasnazany *et al*., 2021). Li *et al*. (2024) reported significant variations in tomato quality traits across different cultivars, highlighting the key role of genotype and ripening stage in determining fruit quality.

Despite numerous studies on tomato quality, there remains a need for comprehensive evaluations that integrate multiple traits across ripening stages to identify cultivars suitable for both fresh consumption and processing. Such evaluations can provide practical guidance for breeders and producers and contribute to the development of cultivars with high yield potential, desirable quality traits, and market adaptability.

Hybrids developed from elite parental combinations can exhibit enhanced disease resistance, environmental stress tolerance, higher yields, and improved fruit quality, traits vital for both consumer preference and agricultural productivity. Breeding success hinges on identifying parental lines with strong hybrid production potential. To maximize yield per unit area and meet the increasing global food demands, developing improved cultivars with high yield potential, desirable flavor and aroma, and resistance to pests and diseases is essential. This process relies on assembling diverse germplasm collections and evaluating their genetic diversity, which forms of any breeding program.

Therefore, the objectives of this study were to explore and analyze the phenotypic diversity among selected tomato cultivars, evaluating their fruit yield and quality traits across different growth stages, with the expectation that the observed variation could lead to the identification of superior genotypes and desirable parental lines for future breeding programs, ultimately contributing to the quantitative and qualitative improvement of tomato.

2. Materials and methods

2. 1. Plant materials and growing conditions

This study utilized 25 tomato cultivars from the Seed and Plant Improvement Institute of Karaj, Iran (Table 1). The experiment was conducted in a randomized complete block design (RCBD) with three replications at the research greenhouse of the Plant Production Technology Research Institute, Shahid Bahonar University of Kerman. The seeds were sown in seedling trays in early March 2024. Approximately 40 days after sowing, when the seedlings had developed four to five true leaves, they were transplanted into large plastic pots measuring 44 × 36 × 100 cm, with three plants grown in each pot. The soil mixture for the seedling trays and pots consisted of cocopeat, perlite, and peat moss. Throughout the experiment, the greenhouse's relative humidity ranged between 60% and 80%, and the temperature was maintained between 18°C (at night) and 28°C (during the day). During the experimental period, the greenhouse received natural light, with a photoperiod of approximately 13 hours of daylight and 11 hours of darkness. Irrigation was carried out daily or every other day, depending on the greenhouse conditions and plant requirements, using a drip irrigation system. The electrical conductivity (EC) of the irrigation water was 0.8 dS/m. The chemical fertilizers and the nutrition program for the plants are described in Table 2. It should be noted that all plants were growing upwards by the stake.

Table 1. Tomato genotypes used in this study

No	Genotype name	Country of origin	Company	Type of genotype	No	Genotype name	Country of origin	Company	Type of genotype
1	Dafnis	Switzerland	Syngenta	Hybrid	14	Bernetta	USA	Seminis	Hybrid
2	Izmir	Switzerland	Syngenta	Hybrid	15	SVTD8042	USA	Bayer	Hybrid
3	SVTH4040	USA	Bayer	Hybrid	16	Umagna	Netherlands	Rijk Zwaan	Hybrid
4	SV3725TH	USA	Seminis	Hybrid	17	GS12ty-D	Switzerland	Syngenta	-
5	Arsin	Turkey	Petektar	Hybrid	18	Rio Grande	-	-	OP
6	Aragon	Spain	Antaris seeds(stella seeds)	OP	19	TM10857	Japan	SAKATA	Hybrid
7	Monaco	Thailand	Miller seed	Hybrid	20	Sun6189	Netherlands	Nunhems	Hybrid
8	SV4129TH	USA	Seminis	Hybrid	21	Firmont	Netherlands	Nunhems	Hybrid
9	Bassimo	USA	Seminis	Hybrid	22	Momtaz /RFT112	Switzerland	Syngenta	Hybrid
10	SV8320TD	USA	Seminis	Hybrid	23	Sama	Netherlands	Emmaseeds	Hybrid
11	Maya	Netherlands	Huizer Zaden	Hybrid	24	Sylviana	Netherlands	Enza Zaden	Hybrid
12	SV4224TH	USA	Seminis	Hybrid	25	Goldy	USA	US Agriseeds	Hybrid
13	Oasis	France	HM-Clause	Hybrid					

Table 2. Nutrition table for tomato plants during different growth stages

Growth Stage and usage type	Time of Application	Fertilizer Type	Dosage	Nutrients
Seedling Stage (Foliar spray)	When seedlings have 2 true leaves	Balanced liquid fertilizer (ammonium sulfate+calcium nitrate +potassium sulfate)	1-1.5 g/L (diluted)	Nitrogen, Phosphorus, Potassium
Transplanting (foliar spray)	At transplanting	High Nitrogen fertilizer (20-20-20)	1 g/L	Nitrogen (for foliage growth)
Flowering (Fertigation)	When flowers appear	High Phosphorus fertilizer (10-20-10)	1 g/L	Phosphorus (for flower development)
Fruit Development (Fertigation)	When fruit starts to set	Balanced fertilizer or higher Potassium (10-10-20)	1 g/L	Nitrogen, Phosphorus, Potassium
Micronutrient (Foliar Spray)	2 times, every 14 days during fruit development to ripening	Micronutrient mix (Cu, B, Fe, Mo, Mn)	1 g/L	Copper, Boron, Iron, Molybdenum, Manganese
Amino acid (Foliar Spray)	At fruit ripening and color change	Commercial Complex	1.5 ml/L	Amino acids (for overall plant health)

2. 2. Sampling and measurement of morphological and quality traits

The experiment was conducted over five months, and fruit sampling was carried out at three developmental stages (green, beginning of ripening, and fully ripened), with three fruits collected from each cultivar at each stage. During the growth period and at the end of the experiment, traits such as TSS, fruit pH, fruit color components (a^*, b^*, and L^*), FL, FW, IL, FFW, DFW, FF, and YLD were evaluated. The TSS content of the fruits was measured using a digital refractometer (model PDR-108-1, EZDO, Taiwan). For this, one drop of juice from three randomly selected fruits from each plant was placed on the prism of the refractometer. The device was first calibrated with distilled water, and the TSS was then recorded at 20°C in degrees Brix (Saidi *et al*., 2008). Fruit pH was measured at maturity and immediately after harvest using a pH meter. The fruit color components (a^*, b^*, and L^*) were evaluated using a colorimeter (model TES135A). Fruit firmness (N/cm^2) was measured with a firmness tester (model Lutron FR-5120, Taiwan) equipped with a 0.3 cm diameter piston. Two readings were taken at opposite positions on each tomato fruit (Al-Dairi *et al*., 2021). It is noteworthy that TSS, fruit firmness, and fruit color components were measured at three growth stages: the onset of fruit coloration (S1: green), mid-coloration (S2: beginning of ripening), and full ripening (S3: fully ripened). To measure the fresh/dry weight of tomatoes, after measuring one-fourth of the fresh weight of the fruit, the desired slices were dried in a ventilated oven (Memmert Germany, Model UN 30) at 65°C for 4 days until the dry weight of the fruit was obtained.Fruit length (cm) and Fruit width (cm) were measured with precision in centimeters using a caliper. Internode length (cm) was measured with a ruler. Total yield (g) was calculated by aggregating the yield records from various harvests for each plant in each replication.

2. 3. Data analysis

Analysis of variance (ANOVA) and mean comparisons were performed using Duncan's Multiple Range Test in SAS software. Box plot visualization and correlation analysis were done using the ggplot2 (Wickham, 2016) and corrplot (Wei *et al*., 2017) packages in the R programming environment. The percentage change from the start of fruit coloration to the middle of coloration was calculated using the following formula:

$$Percentage\ Change = \frac{(Value\ at\ Mid\ of\ Coloration - Value\ at\ start\ of\ Coloration)}{Value\ at\ start\ of\ Coloration} \times 100 \quad (1)$$

3. Results

This study evaluated tomato cultivars at three ripening stages: **S1, S2**, and **S3**. Results revealed significant variability among the cultivars at each stage (Table 3), highlighting differences in their ripening dynamics and quality parameters.

3.1. Fruit pH

The pH of the fruit was not influenced by genotype, which indicates the stability of pH in different tomato cultivars against environmental and physiological changes. A study aimed at determining the composition traits of 69 local tomato genotypes, grouped into eight categories, found no significant differences in pH among the groups, an average pH of approximately 4.24 (Figàs *et al*., 2015).

3.2. Color indices

For the a^* index, higher values were observed at full ripeness, with ‘TM10857’ (50.78), ‘Goldy’ (48.63), and ‘RFT112’ (47.62) exhibiting the most intense red coloration. At the green stage, ‘RFT112’ (53.27) and ‘Bernetta’ (52.63) had the highest a^* values, reflecting early carotenoid development (Figure 1). For fresh market purposes, ‘Sylviana’, ‘Goldy’, and ‘Aragon’ are recommended for their vibrant red hues, while ‘Bernetta’, ‘GS12’, and ‘TM10857’ are ideal for processing due to their deep red pigmentation.

For the b^* index, At S1, 'Arsin’ (61.94), ‘Bernetta’ (60.47), and ‘SVTD8320’ (59.91) displayed the highest b^* values, reflecting a more yellowish tone, while ‘Sama’ (30.93) and ‘Dafnis’ (33.14) had the lowest values, signifying deeper green hues. At S2,’ TM10857’ (54.218) and ‘GS12’ (53.42) exhibited prominent increases, indicating rapid carotenoid synthesis, whereas ‘Sun6189’ (33) had the lowest value, suggesting delayed ripening. At S3, most cultivars showed reduced b^* values due to lycopene accumulation, with ‘Goldy’ (41.73) and ‘Bernetta’ (41.79) maintaining a balanced orange-red hue, while ‘Izmir’ (32.48) and ‘Umagna’ (33.34) developed stronger red coloration (Figure 1).

The L^*color index, representing lightness, is a vital parameter in assessing tomato appearance, where higher values indicate lighter colors and lower values reflect darker shades (Pandurangaiah *et al*., 2020). At the S1 stage, cultivars like ‘Sun6189’ and ‘GS12’ exhibited the highest L^* values, indicating lighter green tones, while ‘RFT112’ and ‘Sylviana’ had the lowest values, suggesting darker green pigmentation (Figure 1). During the S2 stage, L^* values generally decreased as fruits transitioned from green to red and orange hues. The red coloration of tomato fruit is primarily due to the accumulation of lycopene, which occurs predominantly in the final ripening stage (Felföldi *et al*., 2022). Cultivars such as ‘Umagna’ and ‘Goldy’ maintained higher L^*values, representing lighter appearances, while ‘Sylviana’ and ‘Oasis’ displayed darker hues due to earlier lycopene synthesis. At the S3 stage, most cultivars exhibited further decreases in L* values as pigmentation intensified, resulting in darker red fruit. ‘Sun6189’ and ‘Rio Grande’ retained higher L^* values, indicating a brighter red color, while ‘Firmont’ and ‘Sama’ had the lowest values (Figure 1), reflecting deep red tones preferred for processing.

3.3 Total soluble solids

TSS values showed significant variation among cultivars, with the highest values recorded at full ripeness, as expected due to increased sugar accumulation. At the green stage, TSS values were generally low, with the highest value recorded in ‘Sylviana’ (3.43). Cultivars like ‘SV4224’ (0.40) and ‘Bassimo’ (0.42) had the lowest TSS values. During the beginning of ripening, TSS values increased as sugar production began to rise. Cultivars like ‘Sylviana’ (3.62) and ‘TM10857’ (3.53) exhibited the highest TSS values (Figure 1), reflecting a good sugar accumulation at this stage. At full ripeness, TSS values reached their peak in most cultivars, indicating the completion of the ripening process and the highest sugar content. Cultivars such as ‘Sylviana’ (4.04), ‘TM10857’ (4.2), and ‘Umagna’ (4) had the highest TSS values, making them ideal for fresh consumption and processing. Cultivars like ‘Sama’ (2.77) and ‘Izmir’ (2.73) had relatively lower values, which could indicate they are less sweet but may have other desirable qualities for specific markets. Previous studies have also reported substantial variation in TSS across tomato genotypes (Khan *et al*., 2024; Prakash *et al*., 2019; Waiba *et al*., 2021), supporting the genetic basis for this trait’s variation.

3.4. Fruit firmness

At the green stage, cultivars such as ‘Bernetta’ (20.23), ‘Bassimo’ (20.1), and ‘Umagna’ (19.04) exhibited the highest firmness values (Figure 1), indicating that they are firmer at the early stages of growth. During the beginning of ripening, firmness generally decreased across cultivars. ‘Bassimo’ (14.87) and ‘SV4129TH’ (12.67) maintained higher firmness than other cultivars. At full ripeness, firmness values continued to decrease, with ‘Maya’ (5.64), ‘Oasis’(5.70), and ‘Sylviana’ (5.91) showing the softest fruit, which is characteristic of overripe or very mature tomatoes. Cultivars like ‘Bassimo’ (10.03), ‘SV4129TH’ (12.04), and ‘SVH4040’ (9.76) retained moderate firmness, suitable for longer shelf life and better handling.

3.5. Yield, fruit size, fresh and dry weight of the fruit

Significant differences in YLD were observed, with ‘SV3725’ and ‘RFT112’ showing the highest values (Table 3, Figure 1), while ‘RFT112’ also demonstrated relatively high TSS at the end of ripening. In terms of fruit length, ‘Rio Grande’ exhibited the longest fruit, whereas ‘Arsin’ and ‘GS12’ had the shortest. Fruit width varied among cultivars, with ‘Oasis’ and ‘SVTD8320’ producing the widest fruits. Fresh fruit weight was highest in ‘SV3725TH’ and ‘SVTD8042’, with values of 25.5 and 20.59, respectively, while ‘TM10857’ and ‘Bernetta’ had the lowest. Similarly, dry fruit weight was greatest in ‘SV3725TH’ and ‘SV4224TH’, whereas ‘Bernetta’ had the lowest.

Table 3. Analysis of variance (ANOVA) results for the measured traits in tomato.

Source of Variation	Df	Mean Squares							
		pH	TSS-S1	TSS-S2	TSS-S3	FF-S1	FF-S2	FF-S3	a^*-S1
Replication	2	0.08	0.31	0.03	0.51	0.01	0.70	11.05*	158.20*
Treatment	24	0.08	1.52**	0.94**	0.93**	20.21**	10.52**	9.98**	584.73**
Error	48	0.06	0.46	0.40	0.41	3.55	3.64	3.25	96.63
CV (%)	-	5.19	41.09	26.45	20.14	12.41	19.16	22.05	36.04

S1: green stage, S2: beginning of ripening stage, S3: fully ripened stage, TSS: total soluble solids (Brix), FF: fruit firmness (N/cm^2), a^*: redness, CV: coefficient of variability.
*: Significant at the 0.05 probability level, **: Significant at the 0.01 probability level.

Table 3. Continued.

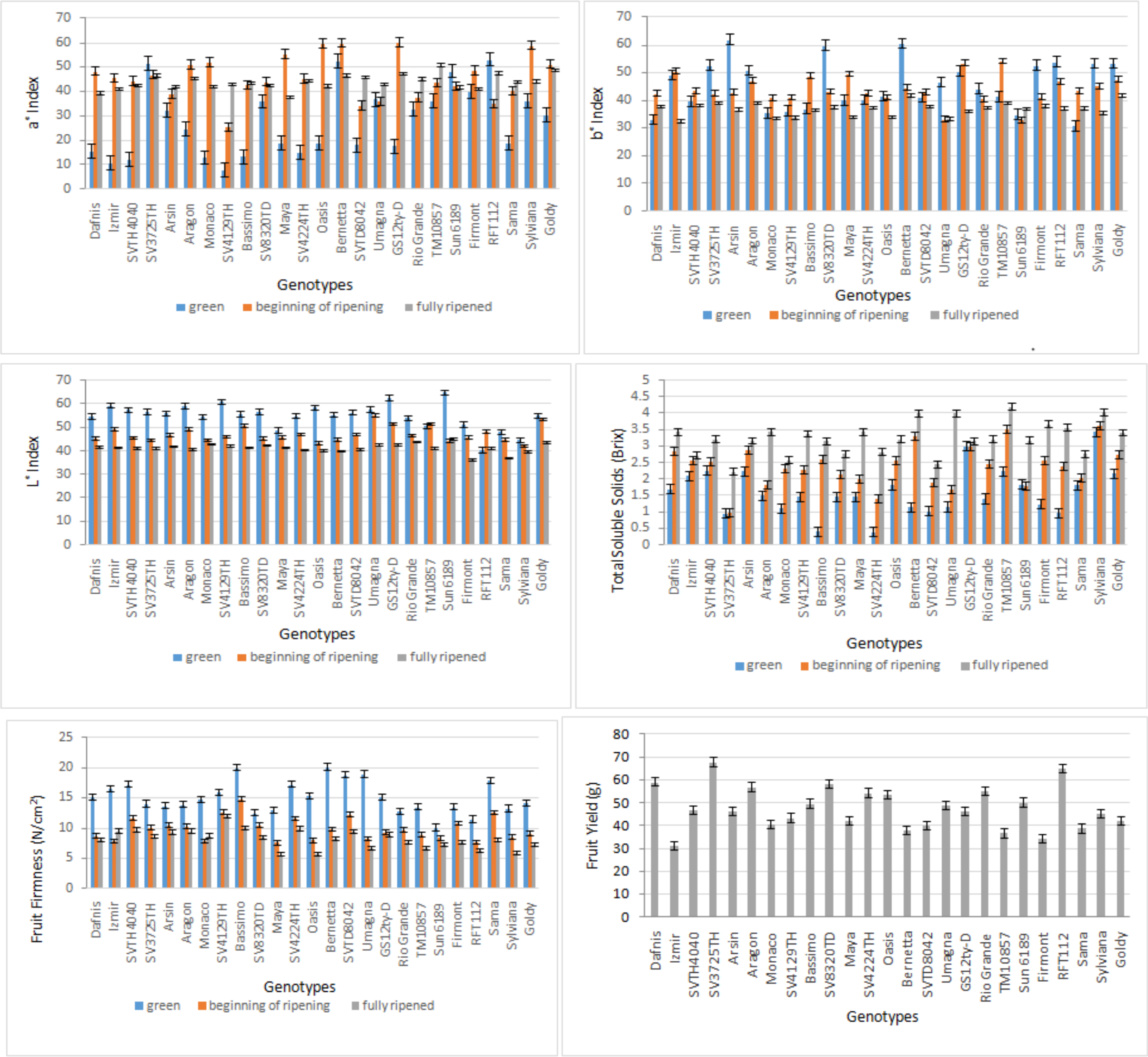
Source of Variation	Df	Mean Squares							
		a^*-S2	a^*-S3	b^*-S1	b^*-S2	b^*-S3	L^*-S1	L^*-S2	L^*-S3
Replication	2	545.49**	21.52	495.67*	30.23	51.41	12.90	5.03	5.20
Treatment	24	220.95**	26.51**	316.18**	93.33**	24.99**	74.62**	29.65**	9.93**
Error	48	108.62	14.52	153.76	25.17	22	30.44	16.32	4.50
CV (%)		22.72	8.64	26.27	11.18	12.91	9.96	8.56	5.13

S1: green stage, S2: beginning of ripening stage, S3: fully ripened stage, a^*: redness, b^*: yellowness, L^*: lightness, CV:coefficient of variability. *: Significant at the 0.05 probability level, **: Significant at the 0.01 probability level.

Table 3. Continued.

Source of Variation	Df	Mean Squares					
		IL	FL	FW	FFW	DFW	YLD
Replication	2	81.22	0.01	0.15	54.84**	0.16*	8.01
Treatment	24	247.05**	0.96**	0.67	26.54**	0.16**	265.76**
Error	48	66.77	0.23	0.43	10.20	0.04	100.01
CV (%)		27.41	10.59	14.19	19.99	19.17	20.93

IL: Internode length (cm), FL: Fruit length (cm), FW: Fruit width (cm), FFW: Fresh fruit weight (g), DFW: Dry fruit weight (g), YLD: fruit yield (g). *: Significant at the 0.05 probability level, **: Significant at the 0.01 probability level.



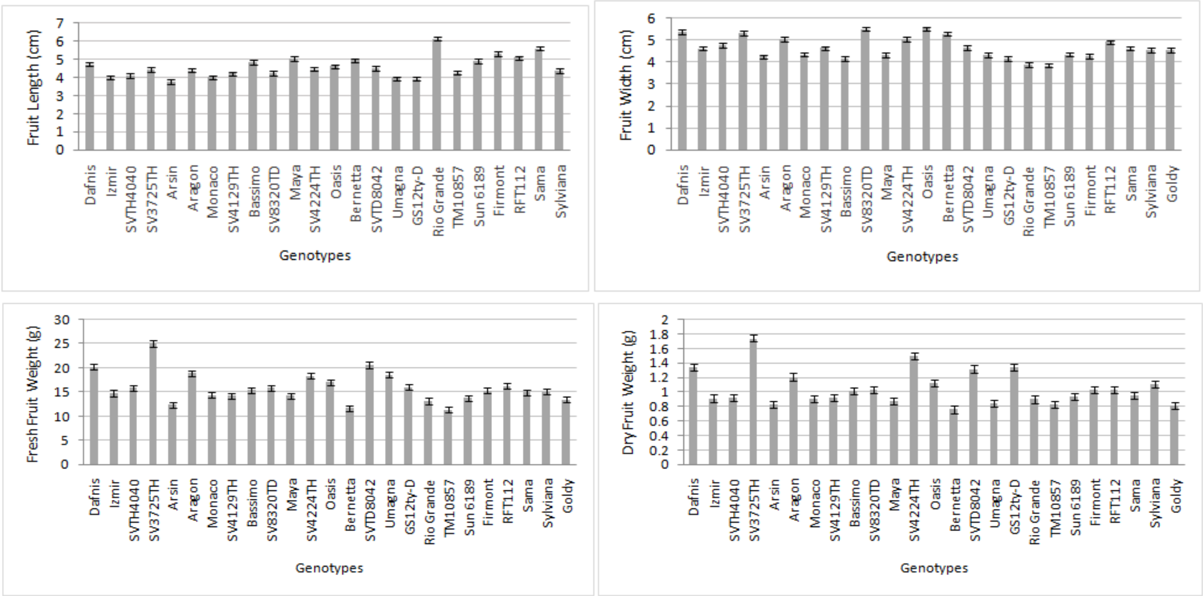


Figure 1. Bar chart illustrating fruit quality-related traits at different growth stages: green stage (blue), beginning of ripening (orange), and fully ripened (gray), alongside yield-related traits.

3.6. The process of changes during different stages of fruit coloration

The results of the measured traits (a^*, b^*, L^*, TSS, and FF) at different stages of fruit coloration (S1, S2, and S3) are summarized in Table 4, along with their percentage changes between stages of coloration. The average a^* index value at the start of coloration (S1) was 27.67. During S2, the a^* value increased significantly to 45.97, representing a 66.17% increase compared to the green stage. However, by S3, the a^* value slightly decreased to 43.93, reflecting a 4.45% decline compared to S2. Similarly, the b^* index and L^* index exhibited trends comparable to those observed in the a^* index.

TSS increased markedly during coloration, showing a 48.52% rise from the green stage to the beginning of ripening and a 35.32% increase from S1 to S2. Firmness decreased significantly as coloration progressed, with reductions of 34.72% and 17.06% during the respective stages.

Table 4. Percentage of variation in different traits at different fruit coloration stages of tomato growth.

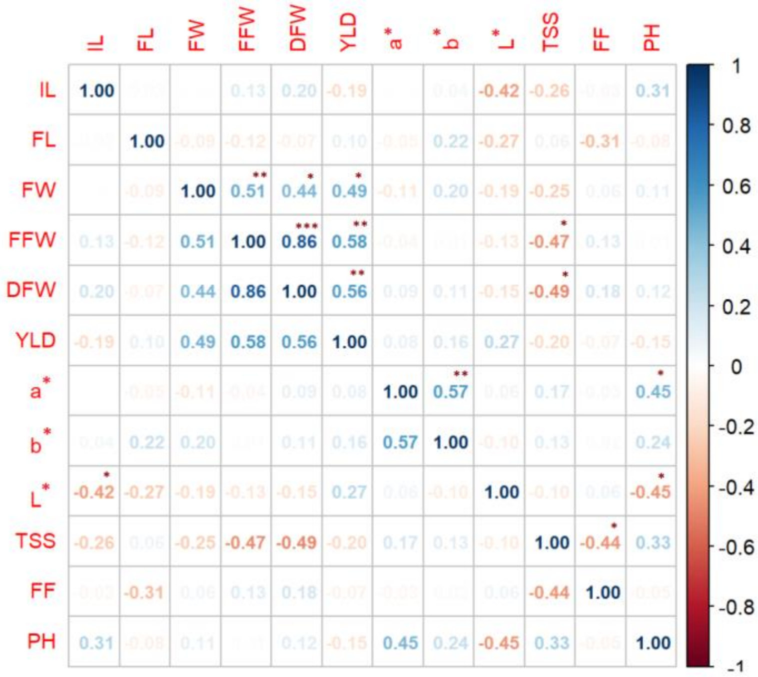
Mean values of traits at different fruit coloration stages	Stage		
	Green	Beginning of ripening	Fully ripened
a^* (redness)	27.67	45.97	43.93
b^* (yellowness)	45.68	44.15	36.88
L^* (lightness)	55.02	47.26	41.35
Total soluble solids	1.62	2.4	3.25
Fruit firmness	15.23	9.94	8.25

Percentage changes in traits between fruit coloration stages

Trait	From green to the beginning of ripening (%)	From the beginning of ripening to fully ripened (%)
a^* (redness)	66.18	-4.45
b^* (yellowness)	-3.35	-16.46
L^* (lightness)	-14.11	-12.51
Total soluble solids	48.52	35.32
Fruit firmness	-34.72	-17.06

3. 7. Correlation between traits at the fully ripened stage

The correlation analysis of the measured traits in tomato cultivars reveals significant relationships that can guide breeding and cultivar selection. Positive correlations were observed between FW and fresh fruit weight (FFW; r = 0.51**) and between FW and dry fruit weight (DFW; r = 0.44*), indicating that wider fruits contribute to higher weights (Figure 2). Similarly, a strong correlation was noted between FFW and DFW (r = 0.86***), as well as between FFW and total yield (YLD; r = 0.58**), suggesting that heavier fruits contribute to higher yields. The a*index and b* index showed a positive correlation (r = 0.57**), highlighting the interdependence of color traits important for market appeal. Negative correlations were found between TSS and FFW (r = -0.47*) and between TSS and DFW (r = -0.49*). A study aimed at evaluating the fruit quality of tomatoes at six growth stages found a positive and significant correlation between soluble solids and fruit pH. They also reported a negative correlation between soluble solids and fruit firmness (Huang *et al*., 2018), which aligns with the present study's findings. YLD showed a positive correlation with the FW (r=0.49*), FFW (r=0.58**), and DFW (r=0.56**). Two different studies reported a positive and significant correlation between fruit width and tomato fruit yield (Henareh *et al*., 2015; Lee *et al*., 2020). The firmness index showed a negative correlation only with the TSS and no significant correlations were observed with other traits (Figure 2).



	IL	FL	FW	FFW	DFW	YLD	a*	b*	L*	TSS	FF	PH
IL	1.00	[illegible]		0.13	0.20	-0.19		0.04	-0.42	-0.26	-0.03	0.31
FL	[illegible]	1.00	-0.09	-0.12	-0.07	0.10	-0.05	0.22	-0.27	0.06	-0.31	-0.08
FW		-0.09	1.00	0.51**	0.44*	0.49*	-0.11	0.20	-0.19	-0.25	0.06	0.11
FFW	0.13	-0.12	0.51	1.00	0.86***	0.58**	-0.04	[illegible]	-0.13	-0.47*	0.13	[illegible]
DFW	0.20	-0.07	0.44	0.86	1.00	0.56**	0.09	0.11	-0.15	-0.49*	0.18	0.12
YLD	-0.19	0.10	0.49	0.58	0.56	1.00	0.08	0.16	0.27	-0.20	-0.07	-0.15
a*		-0.05	-0.11	-0.04	0.09	0.08	1.00	0.57**	0.06	0.17	-0.03	0.45*
b*	0.04	0.22	0.20	[illegible]	0.11	0.16	0.57	1.00	-0.10	0.13	[illegible]	0.24
L*	-0.42*	-0.27	-0.19	-0.13	-0.15	0.27	0.06	-0.10	1.00	-0.10	0.06	-0.45*
TSS	-0.26	0.06	-0.25	-0.47	-0.49	-0.20	0.17	0.13	-0.10	1.00	-0.44*	0.33
FF	-0.03	-0.31	0.06	0.13	0.18	-0.07	-0.03	[illegible]	0.06	-0.44	1.00	-0.05
PH	0.31	-0.08	0.11	[illegible]	0.12	-0.15	0.45	0.24	-0.45	0.33	-0.05	1.00

Figure 2. Correlation between the measured traits at the ripening stage in tomato cultivars. IL: internode length, FL: fruit length, FW: fruit width, FFW: fresh fruit weight, DFW: dry fruit weight, YLD: fruit yield, a*: redness, b*: yellowness, L*: lightness, TSS: total soluble solids, FF: fruit firmness. *: Significant at the 0.05 probability level, **: Significant at the 0.01 probability level, ***: Significant at the 0.001 probability level.

Discussion

Breeding success largely relies on the identification of genetically diverse parental lines with strong hybrid potential. Exploiting such genetic diversity is essential for developing high-yielding cultivars with enhanced fruit quality, better adaptability, and resilience to environmental stresses (Swarup *et al*., 2021). This study evaluated several tomato cultivars at three ripening stages (green, beginning of ripening, and fully ripened), focusing on traits such as color indices, TSS, FF, YLD, and fruit size. The results revealed substantial variability among cultivars at each developmental stage, aligning with previous reports on genetic diversity in traits such as fruit weight, total soluble solids (TSS) content, yield, and fruit quality attributes (Kasnazany et al., 2021; Li et al., 2024). Careful selection of cultivars based on multiple fruit quality traits including size, firmness, TSS, and color is critical for optimizing both marketability and processing suitability. Following the evaluation of genetic diversity, cultivars were selected according to their key traits. Color analysis showed that cultivars like 'TM10857', 'RFT112', and 'Goldy' developed deep red coloration at full ripeness, making them ideal for both fresh and processed markets. 'Goldy' and 'Bernetta' maintained attractive colors, while 'Izmir' and 'Umagna' had deeper reds suitable for processing. The b^* and L^* indices indicated that cultivars such as ‘Arsin’ and ‘SVTD8320’ transitioned to orange-red hues, appealing to fresh markets, while ‘Firmont’ and ‘Sama’ darkened at full ripeness, favoring processing applications. Colour changes in tomato fruit are strongly associated with carotenoid accumulation (especially lycopene and β-carotene) and chlorophyll degradation, which are genetically and environmentally controlled. For example, the switch from green to red during ripening is mediated by the biosynthesis of lycopene via key enzyme genes (such as PSY, ZDS and CrtISO) and the down-regulation of lycopene cyclases, enabling lycopene accumulation and deep red colour (Li *et al*., 2018; Hu *et al*., 2024; Vardanian *et al*l., 2025). Moreover, use of CIELAB colour indices (L*, a*, b*) has been shown to provide objective indicators of ripeness and fruit quality, beyond visual classification alone (López Camelo and Gómez, 2004.).

TSS, an indicator of sweetness, was highest in ‘Sylviana’, ‘TM10857’, and ‘Umagna’, making them suitable for both fresh consumption and processing. Cultivars like ‘Sama’ and ‘Izmir’, with lower TSS, were better for processed products requiring reduced sugar content. Studies link high TSS to sucrose transporters (Wind *et al*., 2010), aiding sweetness breeding, whereas lower TSS aligns with healthier processed formulations (Zhang *et al*., 2024).

Fruit firmness, important for shelf life (Kumar *et al*., 2022), was highest in ‘Bassimo’, ‘Bernetta’, and ‘Umagna’ at the green stage but declined during ripening,due to cell wall changes (Zhang *et al*., 2024).‘Bassimo’ and ‘SV4129TH’ retained moderate firmness, making them suitable for both fresh and processed markets. Research suggests that genetic modifications, such as CRISPR-Cas9 editing of cell wall genes, could improve firmness without affecting taste (Azeez *et al*., 2024).

High-yield cultivars, including ‘SV3725’ and ‘RFT112’, combined commercial productivity with desirable traits. ‘Rio Grande’ produced the longest fruits, while ‘Oasis’ and ‘SVTD8320’ had the widest fruits, catering to specific market demands. Yield and fruit size correlations emphasized the commercial potential of ‘SV3725’ and ‘RFT112’. The strong association between fruit width, fresh weight, and yield indicates that genotypes with large fruit size and efficient resource allocation can achieve higher productivity. Recent meta-analysis reaffirmed that fruit width and fresh weight are reliable proxies for yield in diverse environments (Cheng *et al*., 2021), validating their use in selection indices. Physiological trends during ripening showed that an increase in a^* value reflected red pigment accumulation, while a decrease in L^* indicated higher lycopene content, beneficial for industrial processing. The gradual increase in TSS highlighted sugar and nutrient conversion, essential for fruit quality, suggesting coordinated metabolic changes that enhance both taste and nutritional value. Softening during ripening, driven by enzymatic and structural changes, emphasized the importance of firmness retention for supply chains, as maintaining textural integrity is critical for postharvest handling and reducing mechanical damage. Overall, these coordinated physiological changes demonstrate the interplay of color, composition, and texture traits, providing valuable insights for breeding programs aimed at optimizing fruit quality for both fresh market and industrial processing. Associations between morphological and physiological traits suggest that simultaneous improvement of yield and processing quality is achievable through integrated selection strategies. Correlation analysis highlighted that FF was mainly influenced by structural factors and TSS rather than appearance traits like color. Positive correlations between YLD, FW, and FFW indicate their significant impact on fruit quality and yield improvement. Consumer preferences were crucial for cultivar recommendations, with a multinational survey revealing that 68% of consumers prioritize visual appeal over size, with darker red tomatoes perceived as more nutritious (Jürkenbeck *et al*., 2020). This preference aligns with the demand for cultivars like ‘Sama’ and ‘Firmont’ in processing markets due to their deep pigmentation and high lycopene extraction efficiency. Cultivars like ‘SVH4040’ demonstrated dual-purpose potential, reinforcing the need for multi-trait selection. A holistic breeding approach integrating genomic, phenotypic, and consumer data ensures cultivars are suited for both fresh and industrial markets (Abewoy, 2017).

Conclusion

This study highlights the importance of selecting tomato cultivars according to market needs. Cultivars such as ‘Sylviana’, ‘TM10857’, and ‘GS12’ are recommended for fresh markets due to high TSS, appealing color, and moderate firmness. ‘Goldy’ and ‘Aragon’ offer a balance of flavor and texture for broad consumer appeal. For processing, ‘Izmir’, ‘Sama’, and ‘Bernetta’ are preferred due to their deep red color and lower TSS, while ‘SV4129TH’ and ‘Bassimo’ combine firmness and color for various processing needs. Dual-purpose cultivars like ‘SVH4040’, ‘SV3725’, and ‘RFT112’ exhibit strong performance in yield, firmness, and TSS. Breeding programs that align cultivar traits with market demands can enhance product quality, consumer satisfaction, and profitability.

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